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Estimating bolt tightness using transverse natural frequencies

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ABSTRACT

Structural health monitoring techniques based on vibration measurements have been receiving large attention in the last decades, including techniques for estimating bolted joint tightness and detecting loosened bolts. Due to the exposure of bolted joints to external forces, the bolts may loosen and therefore affect healthy functioning of the bolted structure. In this work a technique is proposed to estimate the level of bolt tightness and to quantify the tension based on the measured natural frequencies of the bolt, in particular the first transverse natural frequency. An experiment is performed on two structure specimens each clamped with a bolt of different length. The bolts bending vibrations are excited by impacting the bolts head along the transverse direction. The excited transverse natural frequencies are then recorded as the bolts are gradually tightened. The measured frequencies trends are explained by modeling the bolt as a pre-stressed one dimensional beam with elastic supports at both ends. The experimental results are reproduced using an analytical function that expresses the boundaries stiffness in terms of the bolt tension. The sensitivity of the measured bolt first transverse natural frequency demonstrates the potential of this frequency-based technique in estimating bolt tightness.

1. Introduction

Bolted joints are widely used in engineering structures and machine design, like wind turbines, drilling rigs, bridges and engines, just to name a few. When a structure with bolted joints is exposed to dynamic loads in the form of shock, vibration or cyclic thermal loading, the fasteners may turn loose [1]. In the case of vibration loading, when the external force overcomes the clamping friction between the bolt and nut, this leads to a relative movement between these two surfaces to occur which results in loosening of the fastener [2]. Such loosening may lead to structural failures if not discovered in time, which can be catastrophic in safety critical applications. In 2015 a 119 m tall wind turbine located in the Lemnhult wind farm near Vetlanda, Sweden collapsed. The cause was attributed to insufficient clamping forces in the joints, which was overcome by the wind forces. Therefore, a regular checking and documentation of proper bolt tightness is essential for certification and safe operation.

Several methods can be used to estimate bolt tension. These include torque control, angle control, stretch control and the ultrasonic method. Torque control utilizes the torque-tension relation, which is an estimate of how torque provided by the torque wrench is converted into bolt tension [3]. Uncertainties as unknown plastic deformation of the threads, torsion and friction between bolt-head/nut and surface entail a variation in the torque-tension relation of up to 30% [3]. However due to the

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Nomenclature

Dimensional variables

f_i	ith transverse natural frequency the bolt/beam, Hz
$f_{i,cc}$	ith transverse natural frequency of the clamped-clamped beam, Hz
$\widetilde{k}_u$	translational stiffness at beam ends, N/m
$\widetilde{k}_\theta$	rotational stiffness at beam ends, N m
N	tensile axial force (bolt tension, clamping force), N
$\widetilde{x}$	longitudinal coordinate, m
$\widetilde{t}$	time, s
$\widetilde{u}$	beam transverse deflection, m
l	length of the beam, m
E	Young's modulus, N/m^2
I	second moment of area of the beam's cross-section, m^4
EI	bending stiffness, N m^2
ρ	density of the beam, kg/m^3
A	cross-sectional area, m^2
ρA	mass per unit length, kg/m
w_0	characteristic frequency of the beam, rad/s
η	asperity density
β	asperity radius of curvature, m
E^*	composite modulus of elasticity of the material of the two surfaces, N/m^2
σ	composite standard deviation of asperity height distributions, m
d	distance between the two surfaces, m
δ_n	denotes the deformation induced by the force N, m
$\widetilde{k}_n$	normal stiffness
da	infinitesimal area of the ring, m
(ρ, ϕ)	polar coordinates of da in the ring surface
r	inner radius of the bolt-head/nut, m
R	outer radius of the bolt-head/nut, m
δ_θ	deformation induced by tilting of the ring, m
$\widetilde{K}_n$	normal stiffness density, N/m^2
M	total torque about the axis of abscissas, N m
ν	Poisson ratio

Dimensionless variables

x	longitudinal coordinate
t	time
u	beam transverse deflection
p	nondimensional tensile axial force
w	beam transverse frequency
λ, γ	eigenvalues of the full model
$\lambda_{cc}, \gamma_{cc}$	eigenvalues of the clamped-clamped beam
$\lambda_{pcc}, \gamma_{pcc}$	eigenvalues of the pre-stressed clamped-clamped beam
h	normalized gap between the two surfaces
(c_1, c_2, c_3, c_4)	fitting parameters for the normal stiffness
c_θ	coefficient for the rotational stiffness
c_u	coefficient for the translational stiffness

simplicity of the torque wrench, this is still the most used method. The angle control method [4] uses the linear relationship between the rotation angle and axial force in an elastic region; however, it is hard to find the elastic region in an actual experiment. Strain gauges are used in stretch control to determine the elongation during bolt tightening and hereby estimate the bolt tension [3]. The accuracy of the strain gauge is high, however due to the requirement of installing these strain gauges, this method may not be practical in bolted assemblies with many fasteners. A discussion on the various bolt-tightening verification techniques can be found in Ref. [5].

The ultrasonic method utilizes the relationship between acoustic wave velocity and length of the bolt combined with the stress state in bolt [6–8]. A transducer emits an ultrasound impulse from one end of the bolt, and the travel time back and forth of the impulse is then recorded to estimate the tension in the bolt [9]. Most ultrasonic devices in industry use the longitudinal waves to determine bolt tension (mono-wave method); however researchers have been working in using also transverse waves (bi-wave method): A velocity ratio approach, which uses a velocity ratio between the longitudinal and the transverse waves that have different acoustoelastic coefficients, was suggested to estimate the tightening force of a bolt [10]. With this method, the time of flight measurement in the unstressed state is not needed. Ultrasonic techniques have also been used to study contact pressure distribution at the clamped interface of bolted joints [11,12]. It was further shown that ultrasonic reflections from the clamped interface could be used to estimate the progress of relaxation in bolted joints [13]. The ultrasonic method provides a better accuracy compared to the torque wrench, and also determines bolt tension without any impact on the joint stiffness, as opposed to strain gauges. However, besides stress, the method is also influenced by temperature and by plastic elongation of the bolt [14]. There are also some requirements for the method to be used, e.g. the bolt ends must be flat, parallel and have a reasonable surface finish, and bolts with short effective lengths are not suitable.

In recent years, a continuous interest was placed on improving and developing other techniques to assess the loosening/tightening health state of bolted joints. Among these techniques are those based on vibration measurements, where the structural vibration response is analyzed for detecting failure in bolted joints. Todd et al. [15] investigated the effectiveness of monitoring changes in structural frequencies and mode shapes, and found that these properties may not be ideal to track joint functionality loss. Meyer and Adams [16] investigated an impact modulation testing method to identify loose bolts within a structure. They developed a modulation index based on the amplitudes of the side-bands in the response spectrum, and showed that this index increased as the bolt torque decreased. Other methods also exploited the nonlinear dynamics of bolted joints: Amerini et al. [17] investigated a vibro-acoustic modulation method, where two indices were developed to assess the health state of bolted joint; A hyperbolic tangent function was proposed to approximate the experimental data with excellent corre-